What Has Been Learned From Pressure Cores

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Abstract

The advancement of pressure core acquisition and analysis technology in recent decades has enabled detailed imaging and direct measurement of naturally occurring hydrate-bearing sediments and has shed light onto hydrate habits, formation processes, fundamental physical properties, and hydrate deposit responses during gas production. This paper reviews the development and capabilities of the pressure core technology, discusses insights learned from hydrate-bearing pressure cores and inherent limitations of this technology, and concludes with suggestions for potential applications of pressure core technology for investigating hydrate deposits.

Introduction

Methane hydrate, which physically resembles ice, is a crystalline compound of methane gas and water. The stability of methane gas hydrate requires relatively low temperature and moderate pressure conditions, which limit the occurrence of methane hydrate in nature primarily to marine continental slope sediments and in and beneath permafrost. The clathrate structure formed by water molecules hinders repulsion between gas molecules and allows for gas concentrations far in excess of what is possible in water alone: there is approximately one molecule of methane for every six molecules of water in methane hydrate, compared to the solubility of methane in water that is approximately on the order of one in 700 [1].

The methane in naturally-occurring gas hydrate represents a large fraction of the Earth's near-surface mobile carbon, is a potential energy resource [2], is an active element of environmental change [3, 4], and potentially affects large-scale seafloor stability [5]. Hydrate formation can plug hydrocarbon pipelines and production wells [6], but can also be used for hydrogen storage [7], and carbon sequestration [8]. Earlier research on gas hydrates focused on pure hydrate crystals, but the focus in recent years has shifted to hydrates in sediments [9].

Man-made (e.g., drilling, gas production from hydrate) and natural (e.g., climate/sea level changes) disturbances to natural hydrate systems can cause hydrate dissociation, a phase change that entails volume expansion, mass and heat transfer. These processes dramatically affect the bulk properties of hydrate-bearing sediments. Due to the complexities of creating synthetic samples that mimic natural hydrate-bearing sediment, proper characterization of hydrate-bearing sediments requires coring, recovery, manipulation, and testing of samples that have never left gas hydrate stability (under pressure-temperature) conditions. Starting in 1980, and particularly since the mid-1990s, pressure core technology has been developed and greatly advanced to address this need.

Pressure Core Technology

Pressure core acquisition

Seafloor pressure core sampling was initially accomplished by using a plastic (generally PVC) core liner equipped with a ball valve system for sealing [10]. Researchers also tried to sample seafloor specimens and seal them in situ during scuba diving [11]. However, these tools are expected to be operated under relatively low water pressure.

Early attempts to recover pressure cores from deep ocean sediments relied on the Pressure Core Barrel (PCB) used by the Deep Sea Drilling Project (DSDP). Initial versions of the PCB used in the 1970s had very low pressure core recovery rates due to failures with closing the ball valve and maintaining core pressure [12-14]. A modified PCB, developed using lessons learned from earlier PCB versions, had a higher operating pressure of 35MPa and successfully recovered sediments of the Blake Outer Ridge at in situ pressures in 1980 [15].

The next generation pressure corer, the Pressure Core Sampler (PCS), was developed by the international Ocean Drilling Program (ODP) [16]. The PCS was a wire line coring device that retrieved sediments in the manner of a rotary or push corer and was sealed by a ball valve with an operational pressure close to 70MPa [17]. The recovered pressure cores could not be transferred into other chambers under pressure for further testing, and so were utilized primarily for degassing and measurement of total gas content, from which estimates of bulk gas hydrate saturation could be obtained. The first systematic pressure core sampling using the PCS occurred in 1995 during ODP Leg 164 drilling [18, 19].

Sponsored by the European Union's Marine Science and Technology Program, the Hydrate Autoclave Coring Equipment System (HYACE) was developed in the late 1990s, and this tool was designed to allow collected cores to be transferred out of the corer and into a measurement chamber without loss of pressure [20]. This system was designed to cut consolidated sediments by rotary drilling driven by a downhole motor (HRC). The push for post-acquisition core testing capabilities continued with the HYACE In New Tests on Hydrate (HYACINTH) system that included not only the coring tools, i.e., the Fugro Pressure Corer (FPC), the Fugro Rotary Pressure Corer (FRPC), and the Submarine Gas Hydrate Reservoirs (SUGAR) corer (SUCO), but also a series of down-stream core testing and processing equipment [21, 22] that were utilized on ODP Leg 204 in 2002. More recently developed pressure core tools in Germany include the Multiple Autoclave Corer (MAC), first used in 2002, and the Dynamic Autoclave Piston Corer (DAPC), first used in 2003, both allow specimen investigation using X-ray computed tomography (CT) [23]. The pressure core samplers MeBo-Druckkern-Probennehmer (MDP) adapted to the sea floor drill rig (MeBo) were developed for quantifying gas hydrate volumes during the project SUGAR [24].

The Pressure-Temperature Core Sampler (PTCS), employed for investigating the Nankai Trough gas hydrate province by the Japanese National Oil Corporation, was a three-meter-long coring device capable of operating at pressure up to 30MPa [25, 26]. The PTCS system was effective in sandy sediments, yet not designed to be compatible with pressure core analysis tools.

Starting in the mid-2000s, a suite of tools known as the Hybrid-Pressure Core Sampler (Hybrid-PSC) or Pressure Core Tool With Ballvalve (PCTB) family have been used in numerous gas hydrate-drilling programs offshore China [27], India [28], Japan [29]. Concurrently, the HYACE/Fugro FPC and FRPC systems were used offshore Korea [30] and in the Gulf of Mexico [31]. In each of these programs, emphasis was placed not only on recovery of the pressure cores, but the subsequent manipulation and measurement of core properties at pressure.

Pressure core manipulation

To preserve gas hydrate stability, pressure cores need to be retrieved at high pressure from coring autoclaves for further testing or storage; thus, a manipulation system is required to transfer and sub-sample cores while maintaining in situ pressure and temperature conditions. As a major part of the HYACINTH system, the Pressure Core Analysis and Transfer System (PCATS) was designed and deployed to transfer pressure cores from coring autoclaves into testing chambers during the 2002 ODP Leg 204 [21]. Later, the Pressure Multi-Sensor Core Logger (MSCL-P) was developed as an integral component of the PCATS that enables core testing using gamma density, P-wave transducer, and X-ray CT [21]. During pressure core transfers (illustrated schematically in Figure 1), pressure chambers are typically connected by ball valves and quick couplings. After equalizing the inside pressure of the manipulator with the autoclave pressure, pressure cores can be pushed or pulled from one high pressure chamber into another. The transfer system always includes a manipulator to latch and move cores using a precise positioning server. Once the core has been removed from the pressure core autoclave into the manipulator itself, the manipulator can be used to cut and transfer pressure core subsections into testing chambers equipped with various testing sensors.

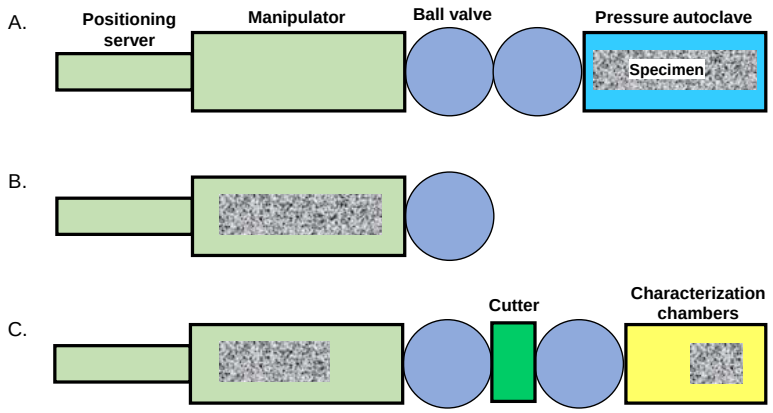

Figure 1: Illustration of typical pressure core manipulation steps. A. The pressure autoclave is connected with an equally pressurized manipulator using ball valves and quick clamps; B. Latching and moving the core from pressure autoclave into the manipulator, followed by closing the ball valve on the manipulator side and removing the autoclave after depressurization; C. Connecting the manipulator with a cutting tool and a pressure core characterization/measurement chamber; after equal pressurization, the core is positioned in the cutter for sub-sampling, then loaded into the characterization chamber for further stand-alone testing.

Pressure core analysis

The PCATS system has been deployed in all pressure core expeditions since the Gulf of Mexico Joint Industry Project (GOM JIP) Leg1 drilling in 2005. The system has evolved from non-destructive analysis of density, p-wave velocity, and X-ray imaging [21] to measuring stress-strain properties and permeability using PCATS Triaxial [22, 32].

The first high pressure measurements by sensors and probes in direct contact with pressure core sediments through perforated core liners was accomplished in GOM JIP Leg1 using a first of its kind high pressure device called the Instrumented Pressure Testing Chamber, IPTC [33]. Immediately after that, an effective stress chamber (ESC) was developed at Georgia Institute of Technology (Georgia Tech) in 2007 to test hydrate-bearing sediments under in situ temperature, pressure, and restored effective stress conditions. The ESC further evolved into a Gas Hydrate Ocean Bottom Simulator (GHOBS) at Korean Institute of Geoscience & Mineral Resources (KIGAM) and was deployed in collaboration with Geotek in 2009 to perform laboratory testing of natural specimens from the UBGH1 expedition [34]. Later, an array of pressure core testing devices called the Pressure Core Characterization Tools (PCCTs) were developed at Georgia Tech [35, 36]. The PCCTs included a manipulator for core transfer, two cutting systems for subsampling, an effective stress chamber (ESC), a direct shear chamber (DSC), a controlled depressurization chamber (CDC), and a microbial reaction chamber (BIO). These tools were designed to measure multiple fundamental properties of natural hydrate-bearing sediments, including stiffness, strength, stress-strain responses, hydraulic conductivity, electrical conductivity, volume change due to hydrate dissociation, and gas production [37].

After the Nankai Trough III drilling in 2012, the Pressure-core Nondestructive Analysis Tools (PNATs) were developed at the National Institute of Advanced Industrial Science and Technology (AIST) for pressure core manipulation and testing. The PNATs can evaluate fundamental hydraulic and mechanical properties of natural hydrate-bearing sediments [38] and include a Transparent Acrylic Cell Triaxial Testing system (TACTT) [39] and a sub-sampler for microscale imaging with an X-ray computed tomography scanner [38, 40].

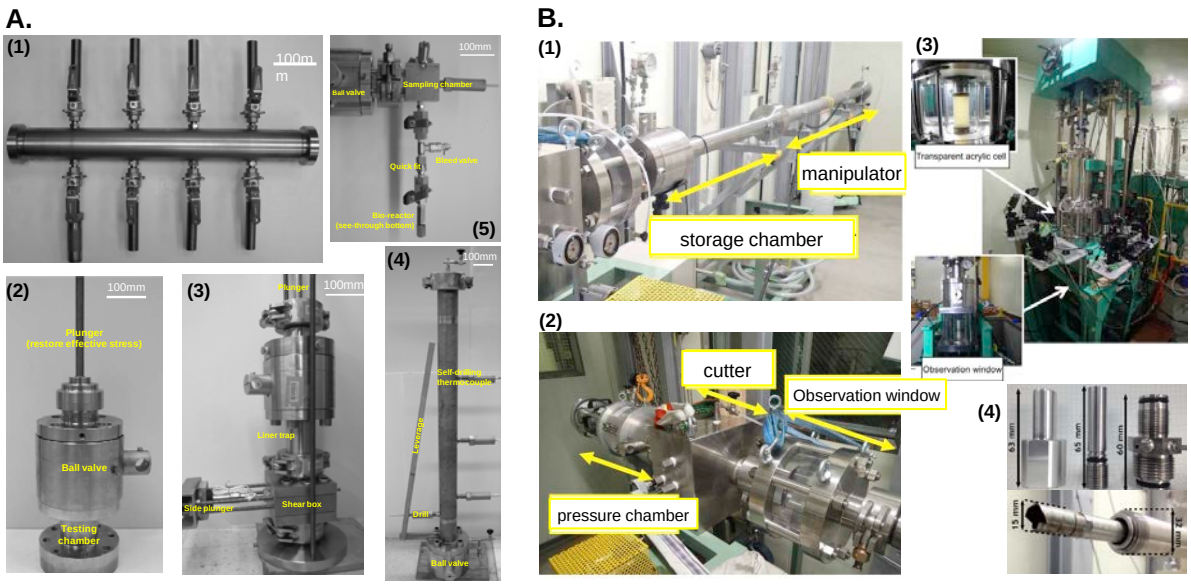

Figure 2: Photos of the developed pressure core characterization tools. (A) The PCCT systems [29-31]: (1) IPTC, (b) ESC, (3) DSC, (4) CDC, (5), BIO. And (B) the PNATs system [32-34]: (1) manipulator, (2) cutter, (3) TACTT, and (4) a sub-sampler for X-ray CT.

Analyses and Discussion

Index properties

Index properties of sediments capture the properties of grain particles and pore constituents, which affect hydrate formation and dissociation characteristics.

Hydrate morphology and pore habits, for instance, are governed by the relative magnitude of skeletal and capillary forces [41, 42], which themselves reflect the in situ effective stress and characteristic pore size. Pressure cores taken in silty-sands (GMGS) and sands (Nankai) have confirmed uniform dispersion of gas hydrate within pore space without observable sediment deformation. However, in fine-grained sediments, capillarity dominates crystal growth, resulting in hydrate forming as nearly pure lenses and veins segregated from host sediments, as revealed with details from X-ray CT images of pressure cores recovered from NGHP-01 [43-45] and UBGH1 [46]. Segregated hydrate lenses in sediments from Gumusut-Kakap [47] and NGHP-01 [48] create a resistivity response that cannot be captured via Archie's equation. Recent observations offshore Japan show that nearly pure hydrates can develop to thickness of tens of meters in certain chimney-shaped sub-seafloor formations in which methane supply into fine-grained sediments has been enhanced [49]. High resolution X-ray CT analyses of UBGH2 pressure cores began to analyze lithological controls on the geometry of grain-displacing hydrate (Figure 3). Note also that some segregated hydrate features are potentially coring induced artifacts in Ulleung Basin pressure cores [46].

In addition to determining the morphology of hydrate in sediment, the mechanical behavior of hydrate-bearing sediments is also inherently governed by intricate interactions among mineral grains, hydrate crystals, and pore fluids. Well-established empirical correlations in hydrate-free sediments can help estimate engineering design parameters [9]. Caution must be employed, however, as certain sediment types that are conducive to hosting gas hydrates, such as diatomaceous fine-grained sediments in Ulleung Basin [46], challenge empirical correlations of plasticity indexes in fine-grained sediments because the presence of diatoms in sediments increases specific surface and plasticity as well as sediment strength and compressibility. Properties that require sediment deformation, such as plasticity, strength and compressibility are of particular concern for pressure core studies of hydrate-bearing sediment because they cannot be easily or systematically studied in situ. Pressure core testing of Nankai Trough specimens provided estimates of the compression index C_c, recompression index C_r, coefficient of volume compressibility m_v, and coefficient of consolidation c_v [37]; yet the index property data are too limited to draw more universal conclusions about how these parameters vary in systems with coarser or finer grain size distributions than were observed in the Nankai Trough system. The Nankai study did highlight the need for future studies to pair

geomechanical index property measurements on hydrate-bearing sediments with measurements on those same sediments after hydrate dissociation. Parameter values for both sediment configurations will need to understand the evolution of a hydrate-bearing formation during production activities.

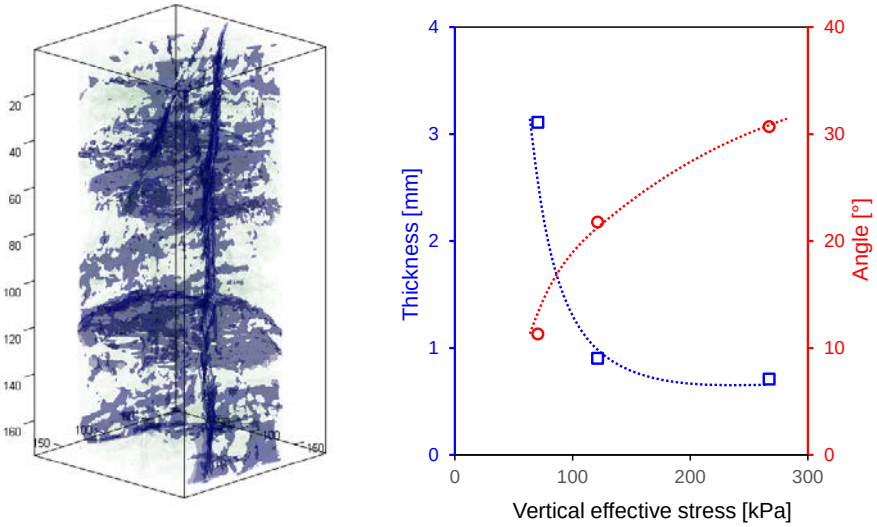

Figure 3: 3D X-ray image of a hydrate-bearing fine-grained pressure core from UGBH2-3. The thickness and dipping angle of hydrate lens in fine-grained sediments are relevant to vertical effective stress.

Stiffness

The small-strain stiffness of hydrate-bearing sediments is mainly governed by the in situ stress state, hydrate saturation, and hydrate pore morphology. P-wave velocity measured using the IPTC for pressure cores recovered from Gulf of Mexico JIP Leg1 [33], NGHP-01 [45], UBGH1 [46], and Nankai Trough [37, 50] are under zero effective stress and thus do not truly reflect sediment stiffness in situ. More accurate in situ stiffness results were obtained by measuring the wave velocities under restored stress conditions using ESC and DSC for UBGH2 and Nankai Trough pressure cores [34, 37]. For coarse-grained sediments with gas hydrate in existing pore space, a P-wave velocity larger than 2000m/s most likely indicates a high hydrate saturation S_h >50% (Figure 4a) even with no effective stress. A set of endmember models is available for linking pore-space hydrate location with wave velocity [51, 52], and as Figure 4 indicates, hydrate appears to occupy existing sediment pore space without cementing the sediment grains together. Corresponding data for grain-displacing, segregated hydrate in fine-grained sediments with high saturations S_h >50% are not available (Figure 4a) but results should largely depend on directivity due to the inhomogeneous, anisotropic nature of hydrates in fines.

The zero-effective stress p-wave velocity in a Nankai Trough pressure core (i.e., core 10P) measured using PCATS one week after coring [53] is slightly higher than that measured at the same spot on the core but 27 weeks after coring using the IPTC [54], demonstrating an aging effect in sediment stiffness. The stiffness decrease during storage of the Nankai Trough pressure core 10P with hydrate saturation S_h = 0.15 developed exponentially with time; sediment in situ stiffness can be restored by re-applying the in situ stress, however [37].

Additionally, gas produced from hydrate dissociation can easily reduce P-wave signatures, hampering efforts to calculate the P-wave velocity, and hence the small-strain stiffness during gas production (Figure 4b, Ulleung Basin pressure core, [35, 45, 46])

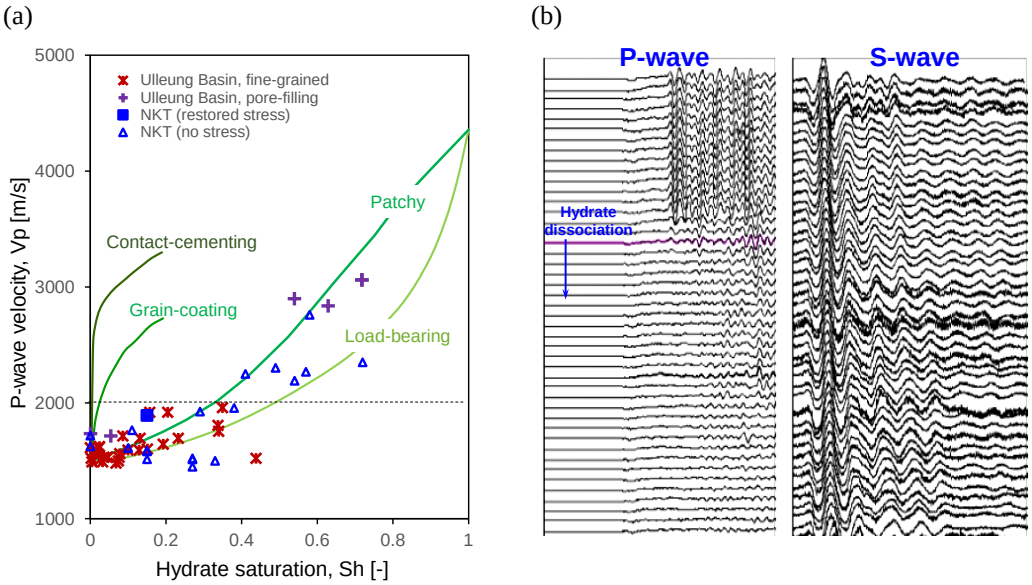

Figure 4: Stiffness of hydrate-bearing sediments pressure cores. (a) P-wave velocity of pressure cores recovered from UBGH2 and Nankai Trough (NKT) [54, 55]. Solid lines are results of rock physical models using material properties under 10kPa effective stress [56-58]. (b) Stacked P- and S-wave traces (initial traces are at the top of each plot and advance downward with time). Pore-space gas generated by hydrate dissociation (occurs at red line) significantly reduces P-wave amplitude and obscures the P-wave measurement (left). Shear waves (right) provide a more robust measure of stiffness changes during dissociation.

Permeability

Permeability, k, shows how the flow rate, Q, through a porous material scales in response to an applied pressure gradient, $\Delta P/\Delta L$, where ΔP is the pressure drop over the distance ΔL. Darcy's law expresses this relation as:

$$Q = k\left(\frac{\Delta P}{\Delta L}\right)\left(\frac{A}{\mu}\right), \tag{1}$$

where A is the cross-sectional area for flow, and μ is the fluid viscosity. Permeability provides a critical control on fluid and gas flow into a well from hydrate-bearing sediment as the formation is depressurized to extract methane from hydrate. Advances in downhole and laboratory measurement techniques have provided new insights and interpretive challenges to quantifying permeability for the purpose of predicting and managing the productivity of hydrate-bearing reservoirs.

The intrinsic reservoir permeability, k_{int}, is relevant for fluid flow through reservoir sediment when water is the only pore constituent. The presence of hydrate in the pore space restricts fluid flow, reducing k_{int} to some effective permeability, k_{hyd}. This effective permeability can be measured in situ with downhole tools, or in the laboratory on hydrate bearing sediment recovered via pressure coring from natural systems. As reviewed by *Fujii et al*. [59] and *Konno et al*. [60], and illustrated in Figure 5, k_{hyd} varies with measurement type even for studies of a single location. Variability between techniques is partly due to how each measurement is carried out. The downhole nuclear magnetic resonance (NMR) measurement provides the only continuous downhole estimate of permeability, but it relies on empirical relations between permeability and the measured relaxation time of magnetically-stimulated pore-space water. Relaxation times reflect effective pore sizes, but are not tied to physical fluid flow in any particular direction. The XPT tool measures permeability by locally decreasing pressure at a borehole-wall contact with the reservoir and then measuring the formation pressure recovery over time as fluid flows into the tool from the formation. This primarily horizontal flow is affected by variations in borehole wall conditions in addition to reflecting properties of the formation itself. Permeability measurements on recovered pressure core specimens are more representative of vertical flow in nature, because they are accomplished by measuring fluid flow perpendicular to the circular cross-section of a core in response to an applied pressure gradient. Relative to the original formation, this vertical flow is affected by any sample disturbance occurring during the acquisition, transfer and storage of the

pressure core specimens.

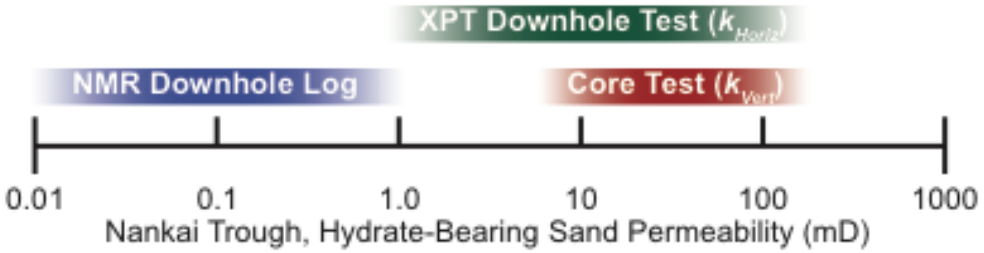

Figure 5: Measured permeability ranges measured through a single sandy, hydrate-bearing layer at the AT1 site in the Nankai Trough, offshore Japan. Measurement locations overlap, so differing results between techniques are likely caused by tool or analysis differences that are not yet fully understood. Caution is urged when choosing a "representative" permeability from field data. NMR results taken from [59], XPT results (green) taken from [60], tests on pressure core material (red) taken from [32, 37, 60].

The potential difference due to sediment fabric orientation between permeability in the horizontal, k_{horiz}, and vertical, k_{vert}, flow directions could systematically offset XPT (primarily horizontal flow), core measurements (primarily vertical flow) and NMR measurements (no explicit flow directionality). At large length scales or in finely interbedded formations when layers of coarse as well as fine-grained material are considered, overall k_{horiz}/k_{vert} ratios of 10 [61] or even 100 [62] may apply. Within a single sediment layer however, lower ratios below 5 may be more appropriate [61, 63], with ratios between 1 and 2 relevant for clean, sandy sediments [63]. A permeability ratio of k_{horiz}/k_{vert} = 10 has been utilized to describe an individual hydrate-bearing layer [64], but this assumption suggests XPT-based permeability should be larger than core-based results, perhaps with NMR results representing an average of the two endmember flow-direction measurements. This relationship is not observed in the case of hydrate-bearing sands in Nankai Trough (Figure 5), though k_{horiz}/k_{vert} = 1-2 as appropriate for clean, sandy sediment would mean the core and XPT results were in general agreement. As noted by *Fujii et al*. [59], additional research will be required to reconcile permeability measurements based on differing techniques to best constrain the true in situ values.

Because permeability is sensitive to the pore-filling material, permeability changes dynamically when methane is extracted from a hydrate-bearing reservoir. Though hydrate dissociation reduces the fraction of pore space occupied by solid hydrate, free gas is produced in the process. Permeability measurements made on pressure core specimens before and after hydrate dissociation show that the coexistence of water and gas interferes with the flow of each phase and can largely offset permeability gains due to loss of solid hydrate from the pore space [37]. This well-known relative permeability phenomenon has been modeled in gas hydrate-bearing sediments using empirical models such as the Brooks-Corey model [65-67]. Additional direct measurements of permeability as a function of gas saturation, and of the sediment's residual gas saturation, are required to establish whether a universal set of model fit parameters exists, or if site-specific parameters must be obtained.

In addition to permeability changes due to evolving pore contents, permeability changes dynamically during methane extraction because of changes to the sediment pore space itself. The primary strategy for destabilizing hydrate and extracting methane is via depressurization of the hydrate-bearing formation. This method, employed in the marine environment at the Nankai Trough [29] and in permafrost environments at the Mallik [68] and Mt. Elbert sites [69], reduces the formation pore pressure, thereby increasing the effective stress on the formation sediment. The effective stress increase, and ensuing loss of solid gas hydrate, leads to settlement (compaction) [37, 70-72]. Settlement lowers permeability by reducing porosity, closing down pore throats and limiting flow pathways. Moreover, variations in sediment grain size, angularity and chemical composition can allow effective stress increases during depressurization to crush sediment grains in spite of the relatively high, ~150 MPa mean strength of sand [61, 73]. Crushed particles can partially fill in pores, simultaneously decreasing pore sizes and increasing sediment surface area, both of which reduce the overall permeability [74, 75].

Fluid and gas flowing toward a production well can also cause permeability reductions. Fine-grained particles ("fines") can swell or be mobilized by the fluid and gas flow, collecting at gas/water interfaces and potentially clogging pore throats [76-78] (See also 'Gas production' Section). Continued depressurization and gas propagation

could fracture such clogs, however [79, 80], and fractures formed in this fashion could increase permeability and enhance flow [81, 82]. These sediment-based mechanisms for permeability alteration will require additional studies of permeability dependence on effective stress and on fines migration in hydrate-reservoir sediments, particularly after hydrate dissociation.

Sampling effects

All laboratory testing of natural sediments is challenged by inherent sampling disturbance. Concerns about sampling disturbances to pressure cores were raised immediately after the first deployment of the IPTC, [33]. Pressure coring, required for obtaining and maintaining hydrate-bearing sediments within the hydrate stability zone, can never completely avoid straining specimens and imparting stress changes during drilling, core recovery, transportation, and specimen preparation for testing (Figure 6a). Finite element method (FEM) analyses of the volumetric strain and stress distribution during coring show that sediments may be subjected to failure even before being harvested into the corer (Figure 6b). Core disturbance can mislead or hamper not only material property studies but also morphology studies. X-ray CT images also show that some hydrate features in fine-grained sediments from UBGH1 (Figure 6c) and NGHP-1 are possibly caused by coring. Characterization of the in situ state of hydrate-bearing sediments based on analysis of pressure cores is challenging due to decreased pore pressure during unloading (i.e., Mandel-Cryer effect) and subsequent hydrate dissociation, secondary hydrate formation, changes in hydrate saturation due to pressure and temperature changes during testing, and relaxation and aging effects [45, 46, 83]. An extensive research effort is needed to quantify the extent to which sampling disturbances impact measured physical property results for hydrate-bearing sediments, as each property is likely to be impacted differently by a given type of disturbance. Ideal sampling should be able to maintain pressure, temperature, and effective stress constantly and with the least stress and straining imposed on sediments during coring.

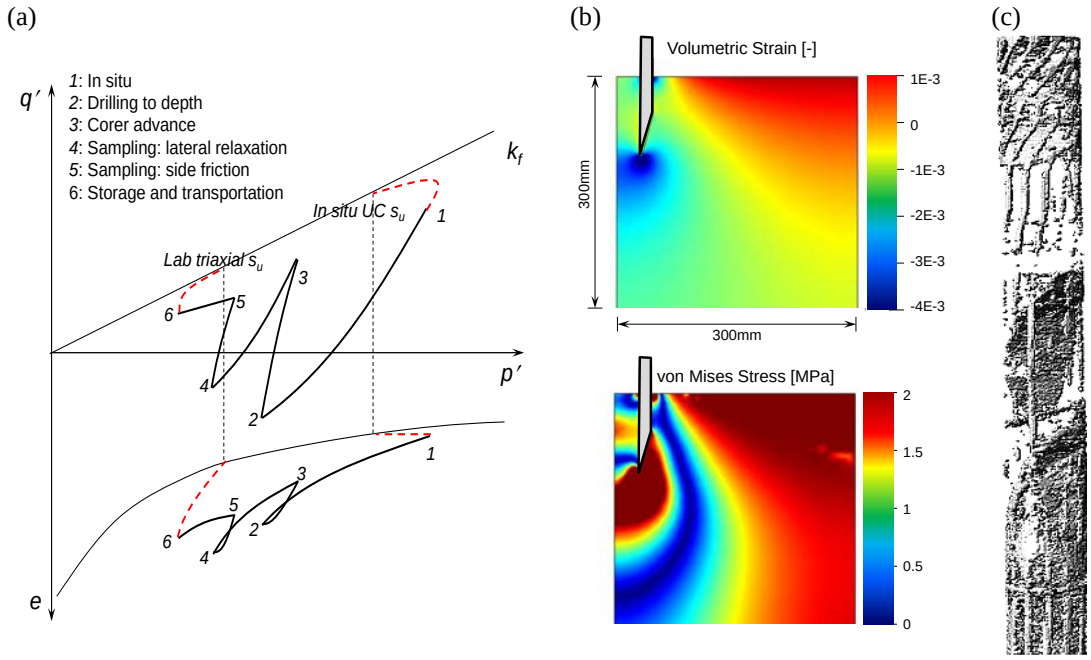

Figure 6: Sampling disturbances. (a) Illustration of stress-porosity paths during sampling; updated from [84], where *q'* is the deviatoric stress, *p'* is the mean effective stress, *e* is the void ratio, and k_f is the failure line. (b) FEM simulation of volumetric strain and stress field during coring. Sediments beneath the tip of the cutting shoe is subjected to failure even before being harvested into the corer. Soil properties used in this simulation are Young's modulus E= 2GPa, Poisson's ratio υ= 0.3, density ρ=1900kg/m^3, and yield stress σ_y = 2MPa. (c) 3D X-ray tomogram of pressure core 10B-14R from Ulleung Basin showing striations from the rotary cutting shoe [46].

Gas production

Before pressure core analysis tools were developed, recovered hydrate-bearing pressure cores had to be degassed with no physical testing other than quantifying gas volumes and collecting gas for later geochemical analyses [17,

85]. As gas hydrate dissociates, the pressure and temperature at the dissociation front define the phase boundary for gas hydrate stability given the existing sediment and pore water characteristics. Measurements at the dissociation front can thus provide insights about lithologic and geochemical environment. The IPTC allowed for the first core-scale production test using an NGHP-1 pressure core, with continuously monitored pressure, temperature, electrical conductivity, P-wave, and gas production rate [45], but without applied effective stress. A similar test was later conducted using a pressure core from UBGH1 [46]. IPTC tests however, utilized point-sensor measurements that captured only local behavior within a portion of the dissociating core. Thus, for example, the measured temperature data only corresponded to the hydrate stability conditions at the dissociation front for the brief time the dissociation front passed the temperature probe. In the IPTC, conditions at the dissociation front could not be tracked over the entire gas production test.

Unlike the IPTC approach, gas production tests of pressure cores from Nankai Trough using the ESC and DSC were conducted under restored in situ stress conditions. Thus, the measured compressibility and settlement induced by hydrate dissociation were closer to expected in situ results. Moreover, since fluids and gas produced during dissociation of these relatively small specimens (compared to those tested in the IPTC) were forced to pass over the temperature sensor as they exited the chamber, the pressure-temperature curves obtained during hydrate dissociation tracked the dissociation-front conditions and followed the hydrate stability phase boundary [37]. Interestingly, the data followed the freshwater phase boundary, likely because even though the original pore fluid was a brine, hydrate dissociation produced fresh water which bathes the dissociation front, which responded as expected in a freshwater system. Gas production tests in the ESC show that much larger settlement can occur when migration of sediment grains during gas production becomes possible [37]. Two specimens (core 8P and 10P) were depressurized from the bottom and the top drainage ports respectively (refer to the setup illustration in Figure 7a). No sediment particles in core 8P were able to be flushed through the porous stone and out of the chamber from the sealed bottom-end depressurization; however, sediment particles were subjected to flushing around the upper porous stone and into the upper part of the chamber along with the water and gas flows during gas production from the top end in core 10P. Thus, hydrate dissociation caused a settlement of only 0.09mm for core 8P, primarily due to the loss of hydrate volume to dissociation, and 1.5mm for core 10P, due to the loss of both hydrate and sediment mass (Figure 7b). The inherent nature of sediment grain migration during gas production by mechanical failure or hydrodynamic erosion remains elusive, in part due to experimental challenges with determining pore pressure, capillarity and effective stress within sediments undergoing active gas production.

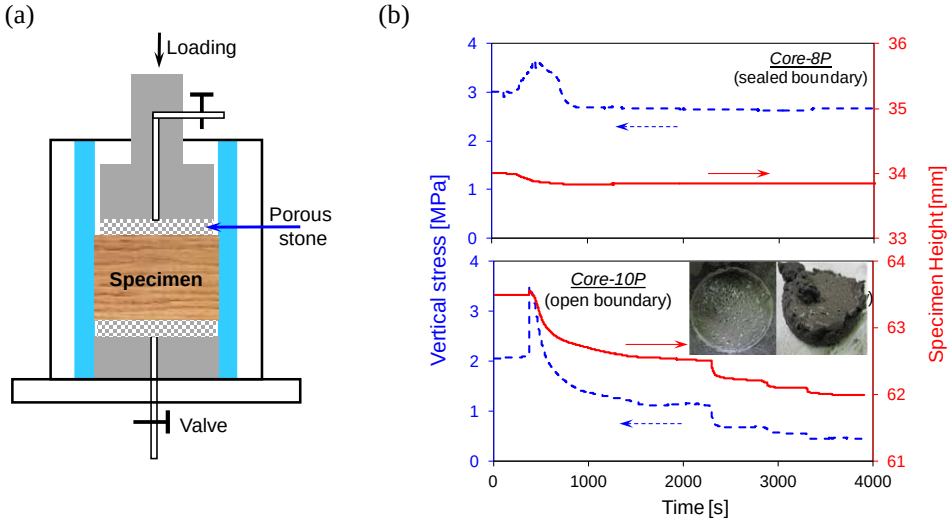

Figure 7: Specimen settlement during hydrate dissociation. (a) Illustration of the ESC chamber setup. The specimen can be depressurized from the top or the bottom drainage port. Porous stones with intricate tiny pore networks allow water and gas to permeate through but not solid particles. (b) Changes in stress and specimen height during gas production for cores 8P and 10P. Insets in core 10P show tiny pockmarks on the top of the core after dissociation (left photo). Sediment particles in core 10P are flushed out of the chamber and re-sediment on top of the upper porous stone (right photo).

Extended capabilities

Existing pressure core characterization tools mainly focus on geomechanical testing at 'quasi-static' conditions. Advancing our capacity to predict dynamic processes, such as calculating the efficiency of depressurizing a hydrate-bearing reservoir to extract methane, or modeling the response of hydrates to geologic shifts in pressure, temperature or pore water chemistry will require characterizing fundamental properties during hydrate dissociation, while phase changes, volume expansion, heat transfer, and mass migration are vigorously occurring. These coupled hydro-thermo-mechanical processes, which manifest themselves as multiphase flow, fines migration, sand production, and rheological behavior of hydrate-bearing sediments, would make for particularly valuable pressure core studies because they would take advantage of the potential for manipulating and deforming the core material in ways that are not yet possible in situ. Pressure core characterization chambers capable of studying chemical and biological processes in hydrate-bearing sediments, including clays, are also needed to address environmental concerns on gas hydrate.

Other major technical challenges for pressure core testing include improved understanding of: sampling disturbances and development of corresponding evaluation methods; enhanced understanding of testing techniques and measured properties; enhanced interpretation of pressure core data combined with information from in situ testing, logging, post dissociation index characterization, and laboratory synthesized specimens; and upscaling techniques to appropriately utilize pressure core data for the design and engineering of gas production from entire hydrate deposits.

Summary and Recommendations

Detailed imaging and direct measurement of naturally occurring hydrate-bearing sediments have been enabled by the development of pressure core, and pressure core manipulation technology, a historical synopsis of which is shown in Figure 8. Early versions of the PCS pressure core acquisition system could achieve high pressure operation up to ~70MPa, but no other compatible high pressure devices were available to the PCS for further testing, except for degassing and quantifying the gas content to infer bulk hydrate saturation. Detailed pressure core analysis became available after the development of the Hybrid-PCS, HYACE and later the HYACINTH systems which included not only the pressure coring capability but also linked to a series of core testing and processing equipment, such as PCATS, the PCCTs, PNATs and TACTT. The latest pressure coring system, the Hybrid-PCS and PCTB, deployed in Nankai Trough III, GMGS 1-4, NGHP-02 and recently modified based on Nankai, Oklahoma, and lab tests, is compatible with IODP and pressure core analysis tools and will be deployed during the UT/DOE Exp-1 project in the Gulf of Mexico.

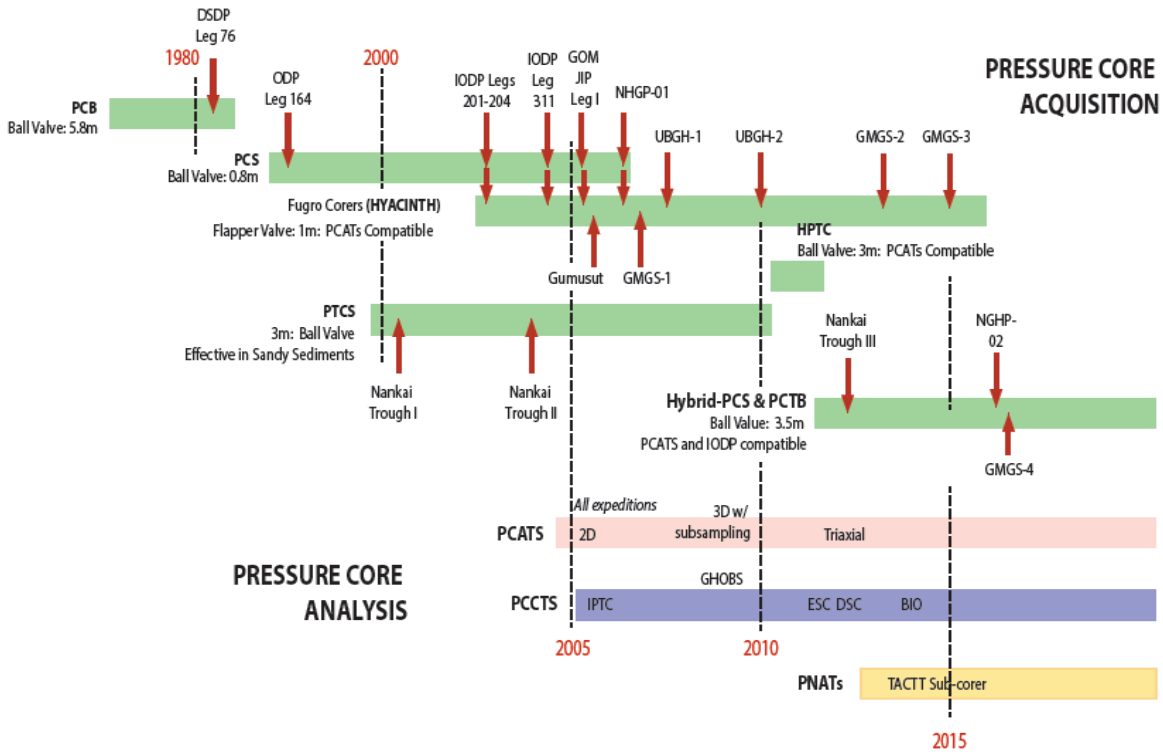

Figure 8: A brief development history of the pressure core technology.

Since the onset of routine pressure core characterization, two important lessons have been learned: (1) sampling effects, particularly caused by stress and straining during coring, may have a significant impact on tested pressure core properties; sampling disturbances were revealed by high resolution X-ray imaging of pressure cores from NGHP-01 and UBGH1&2. Subsequent studies revealed that stress and straining prevail when coring fine-grained sediments with low hydraulic conductivity, and induced poroelastic effects may cause hydrate dissociation and reformation. An ideal coring system should be able to able to continually maintain pressure, temperature and in situ stresses while using cutting shoes designed to minimize rotational or axial straining. Coring should be at a rate no faster than the rate of excess pore pressure dissipation to avoid extra stress and hydrate instability particularly during the acquisition of fine-grained cores; and (2) most of the early physical property measurements were made under virtually no effective stress, which hampers efforts to connect measured properties like stiffness and strength that are stress dependent to their true in situ values. More recently developed ESC, DSC, PCATS Triaxial, and TACTT tools are able to test cores while maintaining pressure and restored in situ effective stress, which makes comparison of pressure core data with LWD and other in situ data possible.

There are several well established empirical correlations for index properties that can be used to estimate engineering design parameters in hydrate-bearing sediments and that can also provide insight into sediment responses during hydrate formation and dissociation. Each new site or lithology provides additional information with which to refine our understanding. For example, from UBGH1 pressure cores, existing empirical correlations on plasticity indexes of fine-grained sediments did not provide accurate fits because of the abundance of diatomaceous sediments in the UBGH1 cores which dramatically increased the surface area, strength, and compressibility of host sediments relative to standard values. ESC testing of Nankai Trough cores began to provide data on how sediment compressibility and volume change indices varied with hydrate saturation. It remains difficult to generalize from the limited lithologies tested thus far and from the limited number of uniform specimens available for destructive testing in those lithologies. However, acquisition, measurement and analysis techniques continue to evolve with each tested specimen, and a greater appreciation has developed for the value of index property data and for measurements made on sediment after hydrate dissociation.

High resolution X-ray imaging of NGHP-01 and UBGH1&2 pressure cores revealed the segregated nature of hydrate in the form of lenses, veins, and nodules in fine-grained sediments. Efforts are needed to further understand

the lithological controls on hydrate formation, morphology, and distribution. Though research may be driven initially by energy resource applications targeting coarse-grained hydrate-bearing sediment, analysis of hydrate-bearing fine-grained cores are also needed to advance our understanding of how hydrate-bearing sediment responds to environmental changes. The laboratory synthesis of hydrate in clays and other fine-grained sediments has been particularly challenging, which puts additional value on pressure cores containing fine-grained hydrate-bearing sediment. Imaging techniques for pressure cores are particularly needed for (1) micro-focus or even higher resolution imaging to reveal hydrate habits in both sandy and fine-grained sediments, such as in South China Sea or Japan Sea cores, and (2) time-lapse monitoring of water, gas, and sediment migration during hydrate dissociation, complemented by other measurements such as stiffness, volumetric change, pore pressure, and thermal and electrical conductivities.

Permeability is one of the most critical controls on gas and water productivity and thus the economic feasibility of producing gas from hydrate deposits. Measured effective permeability differs among different testing techniques. Pressure core permeability results are generally two to three orders of magnitude higher than downhole estimates from NMR logging tools. Even recognizing the importance of differences in flow directions during permeability measurements, the discrepancy in results from various testing techniques and data analyses is not yet fully understood. Devices to measure relative permeability and the impact of sediment migration during hydrate dissociation will be particularly desirable for modeling the evolution and efficiency of a methane production well.

Even ignoring uncertainties due to sampling disturbances, the pressure core data collected to date are not yet sufficient to develop parametric relations of hydrate saturation dependent physical properties. Continued deployment of pressure core technology with extended capabilities are needed. The interpretation of pressure core data requires the consideration of the physical nature of measurements, the spatial position and scale of the sensors and instruments, as well as complimentary information from in situ testing, downhole logging, post-dissociation characterization, and laboratory synthesized specimen testing. Caution is urged when choosing representative physical properties from pressure core tests for field application at larger scales and proper upscaling techniques are indispensable.

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